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3D Coastal Hydrodynamics Model Development Based On Large Eddy Simulation Technique

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Abstract: The 3D coastal hydrodynamics models are mostly adopted RANS technique together with statistical turbulent tools for parameterizing small scale dynamics in the vertical direction. Applying these models in the coastal area where coastal structures exist leads to uncertainty model results due to the presence of LSCS around the structures. Time averaging procedures in the RANS based model remove these features. To tackle this issue, a 3D hydrodynamics model is developed by adopting LES method into FVCOM. Adopting LES concept, the model provides appropriate techniques for representing turbulent term in coastal dynamics. Specific treatment is used to solve anisotropy dynamics in the coastal area by implementing two-eddy SGS closure system. The model is tested for simulating flow over a cylinder under the rough bed scenario. Model validation showed good performance and has capability for capturing turbulent behavior over a cylinder. Using moderate mesh size, the horseshoe vortex, vortex shedding and flow acceleration are represented.

Keywords: Coastal model, LES concept, turbulent flow, coastal area, and turbulent behavior

1 Introduction

Coastal regions are characterized by complex geometry due to the presence of man-made structures such as breakwaters, groins and jetties. When flow passes these structures, Large Scale Coherent Structure (LSCS) from the main flow is extracted and advect the water column (von Carmer and Jirka, 2005). The influence of the vortices is important for the prediction and the evolution of the impact of coastal structural projects in coastal hydrodynamics. A series of work on laboratory experiments, field measurements and numerical models has been done to investigate vortices behavior in the coastal system. For instance, Doron et al. (2002) using submersible Particle Image Velocimetry (PIV) system measured the presence of large-scale vortices from the vertical distribution of mean velocity data at the New York Bight site. The result indicated horizontal eddies have an equal energy level for all elevations while the vertical component is reduced by the bottom. Despite in situ measurement has shown promising result, applying this technique for large scale area is practically not suitable. Hence, numerical models emerge as an alternative technique where the LSCS is represented via parameterization of small scale processes in the vertical direction.

Strictly speaking, the presence of LSCS in numerical models can have a fundamental impact on mixing and coastal circulation (Burchard and Baumert, 2002; Wijesekera, 2003). To obtain the local fluctuations in the main flows, the majority of the models use Reynold Averaging Navier-Stokes (RANS) procedure for solving subgrid closure system (SGS). In this method, the representation of nonlinear properties which arise from advective terms is solved by averaging procedure in time space. Moreover, mean quantities are used rather than a fluctuation as a prognostic variable so that statistical technique is required to extract mean properties of the base flow (Burchard et al., 2008).

RANS based models give an opportunity to include coherent structures in geophysical flows. Such achievement is obtained through simplification method where the local equilibrium assumption is adopted for the second moment equations to improve time simulation. However, such simplification will remove the LSCS and reduces model accuracy. An alternative technique known as Large Eddy Simulation (LES) is used in this paper. LES is based on spatial filtering procedures where the flows are decomposed as large and small scale turbulence. The previous part which defined as containing high energy and non-uniform turbulent is directly solved through spatial filtering while the small scale, less-energy and more uniform is obtained by solving SGS (Rodi, Constantinescu and Stoesser, 2013).

LES application in ocean modelling is relatively new and first research was carried out by Skyllingstad and Denbo (2004) for Langmuir Circulation. LES showed robust performance in this research for representing turbulent and small scale processes. In addition, comprehensive study regarding LES implementation in marine waters is conducted by Scotti (2010). While LES has delivered satisfying result in ocean modelling, adopting LES in coastal modelling is very limited due to the more complex dynamics in horizontal directions.

The flows are subject to mount obstacle on the plane bed where continuously disturbances distributed over the domain. These disturbances induce large-scale eddy structures via re-organizing the Turbulent Kinetic Energy (TKE). The horizontal extent of this structure is significantly larger than water depth and leads to anisotropy issue. To accommodate this feature in the proposed model, two-eddy SGS technique introduced by Roman et al (2010) and Petronio et al. (2013) is used in this paper. It is worth to note that by adopting the LES technique into 3D coastal models provides an opportunity to increase hydrodynamics modelling accuracy and as a basis for turbulent study.

2 Method

2.1 LES concept

$$f = \bar{f} + f' \tag{1}$$

According to Rodi (2013, p. 16) the velocities are decomposed as filtered $\bar{f}$ and fluctuation f' velocity in the LES. The former term represents high-containing energy and directly resolved by mesh size while the latter is represented via the SGS closure system. Quantities with size bigger than the mesh are modelled and categorized as small scale turbulent. Applying this concept into Navier-Stokes equations produces new terms known as Reynold stress. While the equations are mathematically similar to RANS concept, the physical meaning is slightly different. Reynold stress introduced all turbulent term in RANS while only small scale turbulent is represented in the LES. Additionally, mathematical procedures involving time averaging in uniform direction are required to obtain all turbulent term in LES (Argyropoulos and Markatos, 2015).

The success of LES depends on the choice of filtering procedure and SGS capability to reproduce unfiltered term. Moreover, the effectiveness of filtering technique is discussed by Denaro (2011). In this paper, this parameter is used to guarantee so that the filtering procedures solve the turbulent as much as possible.

The LES concept is implemented in unstructured three-dimensional Finite Volume Community Ocean Model (FVCOM) developed by Chen et al. (2003). FVCOM is chosen due to the capability when dealing with complex geometries such requirement is highly needed for coastal simulation. The LES deployment is started by inserting Eq. (1) into FVCOM governing equations;
For the sake of completeness we have rewritten Eq. (1) in the form of velocity.

$$u = \bar{u} + u' \tag{2}$$

The next step is to insert Eq. (2) into filtered form of FVCOM governing equations which composed of the filtered of momentum and continuity equations.
The filtered of momentum equations

$$\frac{\partial \bar{u}}{\partial t} + \bar{u}\frac{\partial \bar{u}}{\partial x} + \bar{v}\frac{\partial \bar{u}}{\partial y} + \bar{w}\frac{\partial \bar{u}}{\partial z} - f\bar{v} = -\frac{1}{\rho_o}\frac{\partial P}{\partial x} + \frac{\partial}{\partial z}\left(K_m\frac{\partial \bar{u}}{\partial z}\right) + F_{\bar{u}} + \frac{\partial \tau_{uSGS}}{\partial x} \tag{3}$$

$$\frac{\partial \bar{v}}{\partial t} + \bar{u}\frac{\partial \bar{v}}{\partial x} + \bar{v}\frac{\partial \bar{v}}{\partial y} + \bar{w}\frac{\partial \bar{v}}{\partial z} - f\bar{u} = -\frac{1}{\rho_o}\frac{\partial P}{\partial y} + \frac{\partial}{\partial z}\left(K_m\frac{\partial \bar{v}}{\partial z}\right) + F_{\bar{v}} + \frac{\partial \tau_{vSGS}}{\partial y} \tag{4}$$

The filtered of continuity equation

$$\frac{\partial \bar{u}}{\partial x} + \frac{\partial \bar{v}}{\partial y} + \frac{\partial \bar{w}}{\partial z} = 0 \tag{5}$$

Where x, y, and z are the axes in Cartesian coordinate; $\bar{u}$, $\bar{v}$, and $\bar{w}$ are the velocity components for x, y, and z coordinates; $F_{\bar{u}}$ and $F_{\bar{v}}$ are the horizontal momentum diffusion terms; K_m is the vertical eddy viscosity coefficient. The new terms in Right Hand Side (RHS), $\frac{\partial \tau_{uSGS}}{\partial x}$ and $\frac{\partial \tau_{vSGS}}{\partial y}$, represent the fluctuations from small scale eddies. These terms emerge as an indication of unresolved quantities which larger than the grid size. Clark et al. (1979) introduced three physical terminologies defined as Leonard L_{ij}, Cross C_{ij}, and Reynold R_{ij} stress.

$$\frac{\partial \tau_{ij}}{\partial x_j} = \frac{\partial}{\partial x_j}\left[\overline{u_i u_j} - \bar{u}_i \bar{u}_j\right] = L_{ij} + C_{ij} + R_{ij} \tag{6}$$

$$L_{ij} = \overline{\bar{u}_i \bar{u}_j} - \bar{u}_i \bar{u}_j \tag{7}$$

$$C_{ij} = \overline{\bar{u}_i u'_j} + \overline{u'_i \bar{u}_j} \tag{8}$$

$$R_{ij} = \overline{u'_i u'_j} \tag{9}$$

L_{ij} represents the interaction in resolving scale, R_{ij} expresses interaction in small scale and the interaction between resolved and unresolved turbulent is defined by C_{ij} term. Furthermore, L_{ij} term can be directly obtained from resolved part while both C_{ij} and R_{ij} are modelled by the SGS closure system.

For the sake of simplicity, Smagorinsky Model (SM) which introduced by Smagorinsky (1963) based on the eddy viscosity concept is adopted as a SGS closure system in this research. It uses similar assumptions as viscous stress in the laminar flow where the characteristic length scale and velocity gradients are used to represent a flow field. However, directly implementing SM for coastal models introduced anisotropy grid issue due to the large scale difference between horizontal and vertical grids. Therefore, SM modification is conducted by adopting a two-eddy concept in geophysical fluid dynamics. Roman et al. (2010) introduced a two-eddy viscosity concept to accommodate the anisotropy issue in the SGS closure system. Two different values of filtering size are presented in two-eddy for both horizontal and vertical directions. The implementation of two-eddy concept is conducted through modification in diffusive term. Here the new diffusive term is defined as:

$$D_i = \frac{\partial}{\partial x_i} \nu_h \frac{\partial \bar{u}_i}{\partial x_i} + \frac{\partial}{\partial x_j} \nu_v \frac{\partial \bar{u}_j}{\partial x_j} \tag{10}$$

i represents the direction in horizontal scale while j describes the direction in the vertical scale. ν_v and ν_h denote for vertical and horizontal eddy, respectively. Sharing similar ideas with SM, characteristic length scale for horizontal L_H and vertical L_V defined as:

$$L_H = C_H \Delta_H \tag{11}$$

$$L_V = C_V \Delta_V \tag{12}$$

Δ_H and Δ_V are proportional to the grid size in horizontal and vertical directions. An improvement from Smagorinsky constant C_S , C_H and C_V can have different value. While this option is a good technique to solve anisotropy issue, the adjustment of these empirical constants produces uncertainty from model result. However, Petronio et al. (2013) showed a procedure to get optimal value for C_H and C_V through the calibration process in elevated grid anisotropy ratio. Fig. 1 described variation to get optimal value for C_H and C_V.

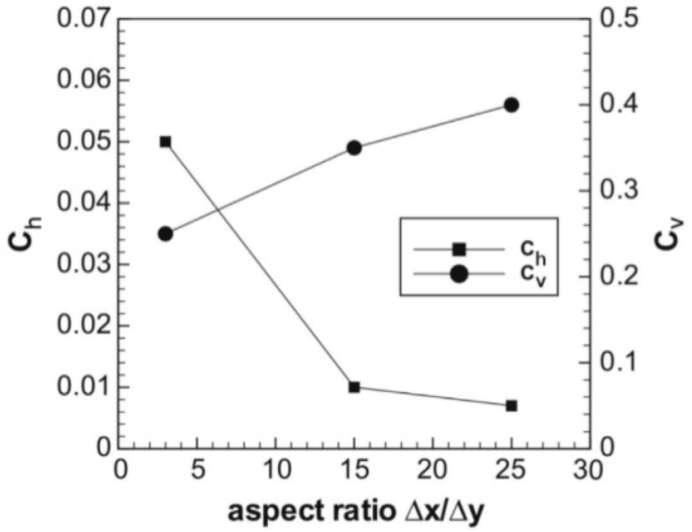

Fig. 1. Optimal value for C_H and C_V

To be consistent with length scale, the strain rate tensor is decomposed as horizontal and vertical part for determining velocity scale. In horizontal direction, the strain rate tensor is defined as

$$|\bar{S}_H| = \sqrt{2\bar{S}_{ii}^2 + 2\bar{S}_{jj}^2 + 4\bar{S}_{ij}^2} \tag{13}$$

while in the vertical direction, it is defined as:

$$|\bar{S}_V| = \sqrt{4\bar{S}_{ik}^2 + 2\bar{S}_{kk}^2 + 4\bar{S}_{jk}^2} \tag{14}$$

i, j, and k stand for vector indexes in x, y, and z direction. Finally, the two-eddy coefficients can be arranged as:

$$\upsilon_H = (C_H \Delta_H)^2 |\bar{S}_H| \tag{15}$$

$$\upsilon_V = (C_V \Delta_V)^2 |\bar{S}_V| \tag{16}$$

3 Result and discussion

3.1 Model domain and setup

Model performance is tested for simulating flow over a cylinder. Its common case in turbulent flow study and has been done by Young and Odoi (2007), Liu (2018), Mittal (1995), Strandenes et al. (2015), Fröhlich et al. (2001), and Roulund et al. (2005) .The test offers simple geometry, but complex processes, namely flow separation, horseshoe vortex and vortex shedding mechanism. Moreover, the emphasis of this case is to identify horseshoe vortex in front of the cylinder, examining the wake formation behind the cylinder and investigate the acceleration area on the sides of the cylinder. The model is validated by using Roulund et al. (2005) experiment data for rough case bed. Model domain is shown by Fig. 2.

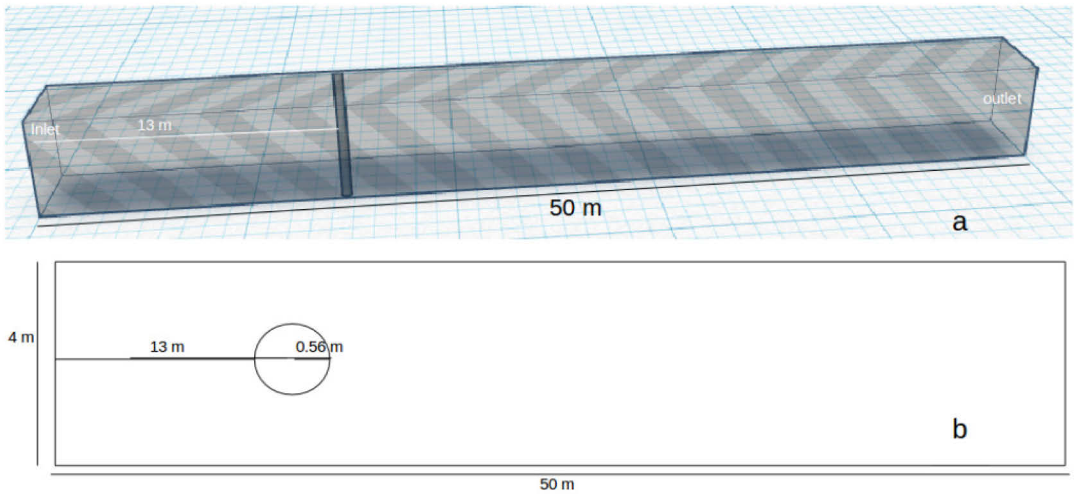

Fig. 2. Model domain

The simulation is conducted in 4 m to 50 m domain with non-uniform mesh size varying from 0.05 m near the cylinder and 0.1 m in another area. Following Petronio et al. (2013) method to obtain optimal model performance, 0.005 and 0.25 values are used for C_H and C_V, respectively. Another parameter can be seen in the Tab. 1.

Tab. 1. Simulation parameters

Parameter	Value
Water depth (m)	0.25
Mean flow velocity (ms^{-1})	0.4
Reynold number	1.8×10^5
Roughness (cm)	1.0
Number of mesh in horizontal direction	93138
Number of mesh in vertical direction	50
Time step (s)	0.001

1.1 Model validation

The average streamwise velocity is compared with experimental data from Roulund et al. (2005) for several depths in Fig. 3. Furthermore, time averaging procedure is conducted by averaging the 120 instantaneous numerical results after the fully developed condition is achieved.

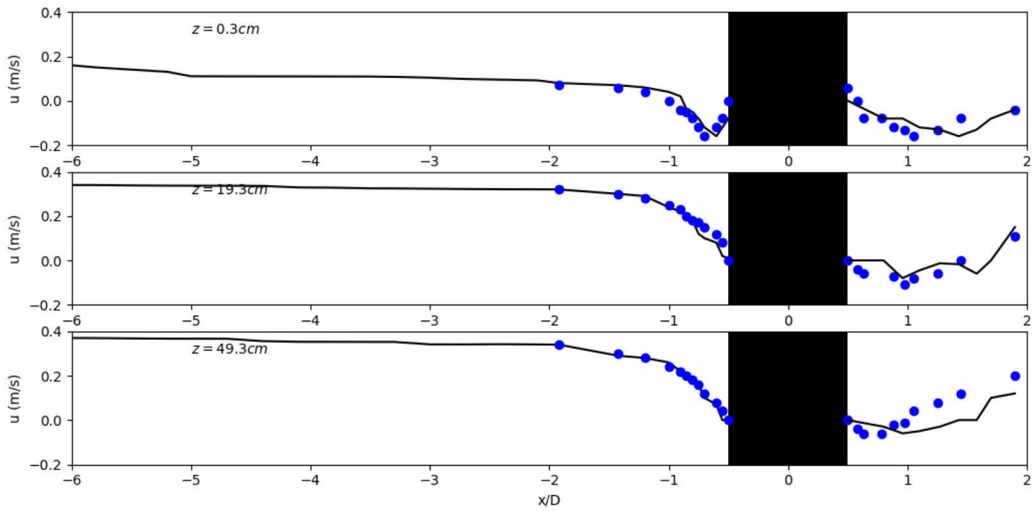

Fig. 3. Profiles of the average streamwise velocity for several depths from the model (solid line) and Roulund (2005) experiment (blue circle).

Fig. 3 shows that model velocities are in good agreement with experimental data. The blue circles in the picture represent Roulund (2005) data and black solid lines are model results. Uniform flows with speed approximately 0.2 m/s are developed from the inlet and these values gradually decrease near the cylinder. Moreover, velocities increase before reaching steady condition at the downstream part. In the vertical directions, velocity increases from surface to the bed following turbulence generation by rough bed.

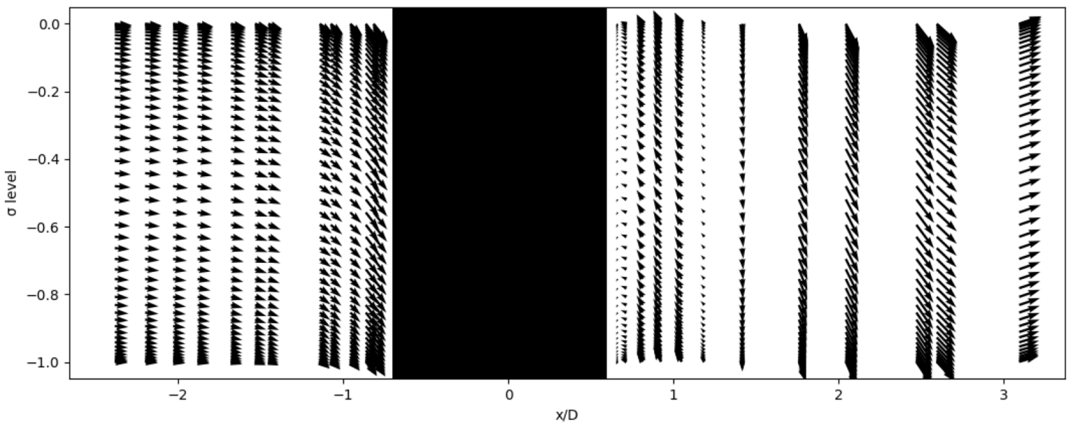

Fig. 4. Vertical velocity profile at z = 0.27 m

The vertical profile represents uniform flows following logarithmic function before change the patch when reaches the cylinder as shown in Fig. 4. At 5 cm upstream to the cylinder, the flows change direction and go down with reducing the velocity. The horseshoe vortex formation is clearly illustrated in this area and similar result also captured by Aghaee and Hakimzadeh (2010). When the flow passes the cylinder, two vortexes are formed. The first is weak-clockwise vortex at 5 cm downstream the cylinder and the last one is strong-anticlockwise vortex. The existence of clockwise vortex is found in past simulation from Yin et al (2014), Aghaee and Hakimzadeh (2010), and Roulund et al. (2005) in rough bed case.

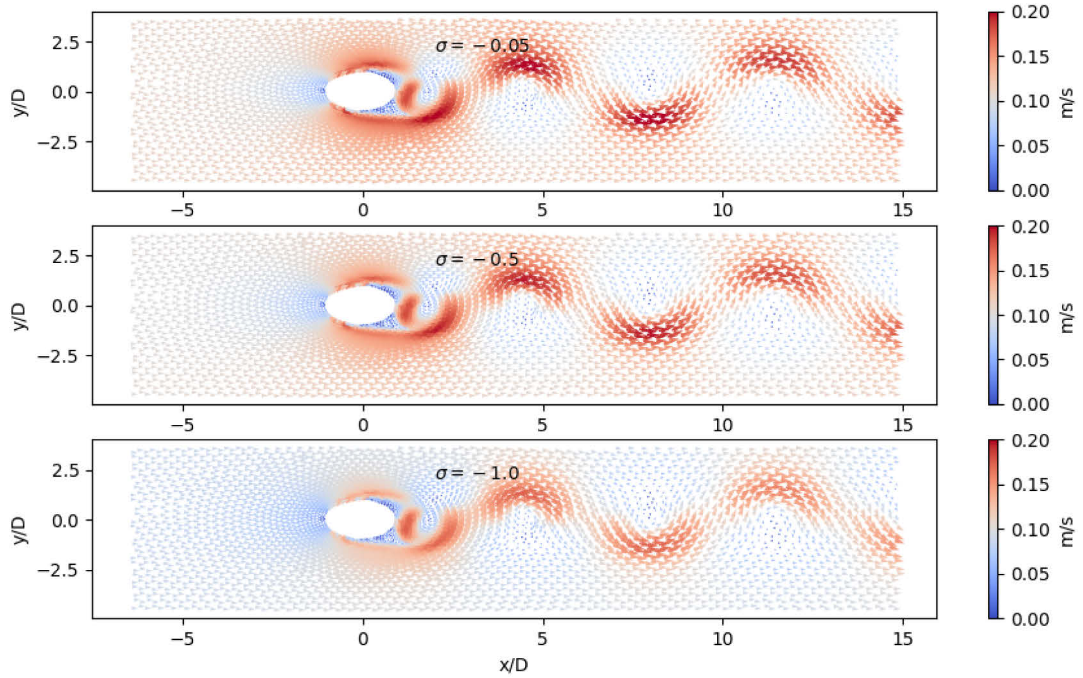

Fig. 5. Instantaneous velocity magnitude for several σlevels

Another important flow structure of this simulation is a vortex shedding. Fig. 5 explained that the vortex-shedding behind the cylinder is periodic. The instantaneous velocity magnitude from different σ levels show that the wake reduces its magnitude from the surface to the bottom. However, the form of vortex-shedding in the wake region is maintained. At the sides of the cylinder, high velocity flows are captured. These flows have a significant role for the vortex-shedding formation behind the cylinder.

Eddies are identified at downstream the cylinder. Eddies grow and travel from one point to another before vanishing. This behavior is the evidence for unsteady wake and it is shown in the Fig. 6. In addition, the horseshoe vortex is captured in front of the cylinder. A similar condition is found in Roulund et al. (2005) for depth z/D = 0.5.

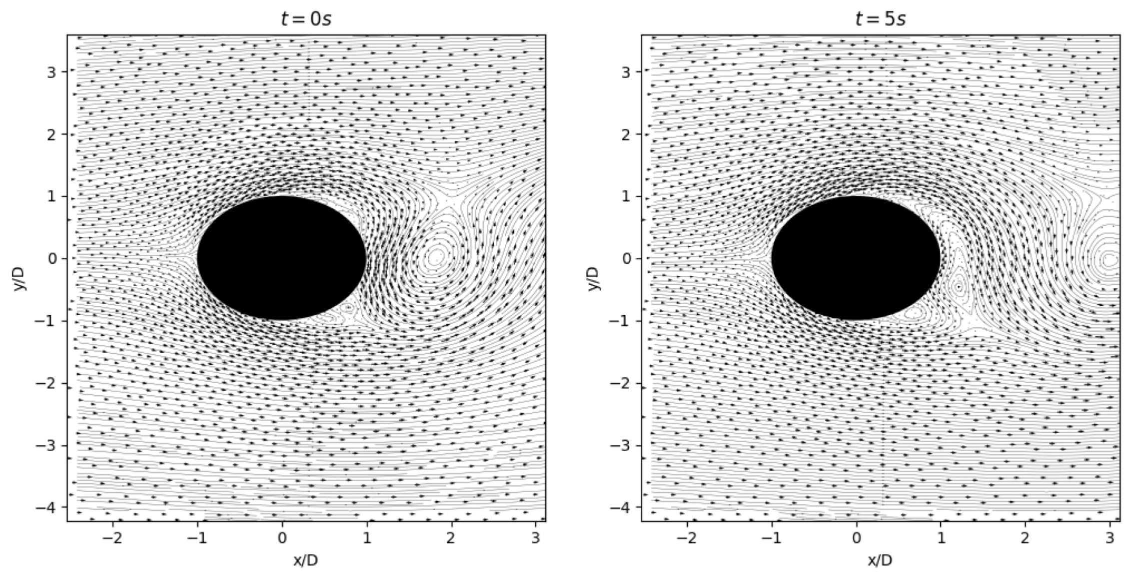

Fig. 6. Streamline of instantaneous velocity at z = 0.27 m

4 Conclusions

A 3D Hydrodynamic model is developed by adopting the LES technique into FVCOM. The two-eddy approach is adopted as a subgrid closure system and as a procedure to overcome anisotropy issue in the model. Model validation indicates good performance for simulating flow over a cylinder for the rough bed case. It showed robust capability in capturing main flow features such as horseshoe vortex, vortex shedding, and acceleration of velocity at the sides of the sphere is produced.

References

Aghaee, Y. and Hakimzadeh, H. (2010) 'Three dimensional numerical modeling of flow around bridge piers using LES and RANS', in *International conference on fluvial hydraulics, river flow*, pp. 211–218.

Argyropoulos, C. D. and Markatos, N. C. (2015) 'Recent advances on the numerical modelling of turbulent flows', *Applied Mathematical Modelling*. Elsevier, 39(2), pp. 693–732.

Burchard, H. *et al.* (2008) 'Observational and numerical modeling methods for quantifying coastal ocean turbulence and mixing', *Progress in Oceanography*, 76(4), pp. 399–442. doi: 10.1016/j.pocean.2007.09.005.

Burchard, H. and Baumert, H. (2002) 'The Formation of Estuarine Turbidity Maxima Due to Density Effects in the Salt Wedge. A Hydrodynamic Process Study', *Journal of Physical Oceanography*, 28(2), pp. 309–321. doi: 10.1175/1520-0485(1998)028<0309:tfoetm>2.0.co;2.

von Carmer, C. F. and Jirka, G. H. (2005) 'Shallow Turbulent Wake Flows: Momentum and Mass Transfer due to Large-Scale Coherent Vortical Structures', *Institu fuer Hydromechanik*, (June), p. 390. doi: 10.5445/KSP/1000003453.

Chen, C., Liu, H. and Beardsley, R. C. (2003) 'An unstructured grid, finite-volume, three-dimensional, primitive equations ocean model: Application to coastal ocean and estuaries', *Journal of Atmospheric and Oceanic Technology*, 20(1), pp. 159–186. doi: 10.1175/1520-0426(2003)020<0159:AUGFVT>2.0.CO;2.

Clark, R. A., Ferziger, J. H. and Reynolds, W. C. (1979) 'Evaluation of subgrid-scale models using an accurately simulated turbulent flow', *Journal of fluid mechanics*. Cambridge University Press, 91(1), pp. 1–16.

Denaro, F. M. (2011) 'What does Finite Volume-based implicit filtering really resolve in Large-Eddy Simulations?', *Journal of Computational Physics*. Elsevier, 230(10), pp. 3849–3883.

Doron, P. *et al.* (2002) 'Turbulence Characteristics and Dissipation Estimates in the Coastal Ocean Bottom Boundary Layer from PIV Data', *Journal of Physical Oceanography*, 31(8), pp. 2108–2134. doi: 10.1175/1520-0485(2001)031<2108:tcadei>2.0.co;2.

Fröhlich, J. *et al.* (2001) 'Large Eddy Simulation of Flow around Circular Cylinders on Structured and Unstructured Grids, II', *Numerical Flow Simulation II*, pp. 231–249. doi: 10.1007/978-3-540-44567-8_14.

Liu, H. (2018) 'Large eddy simulation of flow past a 3D cylinder at Re=3900', *IOP Conference Series: Materials Science and Engineering*, 383(1). doi: 10.1088/1757-899X/383/1/012050.

Mittal, R. (1995) 'Large-eddy simulation of flow past a circular cylinder', *Annual Research Briefs*, pp. 107–116.

Petronio, A. *et al.* (2013) 'Large eddy simulation model for wind-driven sea circulation in coastal areas', *Nonlinear Processes in Geophysics*, 20(6), pp. 1095–1112. doi: 10.5194/npg-20-1095-2013.

Rodi, W., Constantinescu, G. and Stoesser, T. (2013) *Large-eddy simulation in hydraulics*. Crc Press.

Roman, F. *et al.* (2010) 'Large eddy simulation of mixing in coastal areas', *International Journal of Heat and Fluid Flow*. Elsevier Inc., 31(3), pp. 327–341. doi: 10.1016/j.ijheatfluidflow.2010.02.006.

Roulund, A. *et al.* (2005) 'Numerical and experimental investigation of flow and scour around a circular pile', *Journal of Fluid Mechanics*, 534, pp. 351–401. doi: 10.1017/S0022112005004507.

Scotti, A. (2010) 'Large eddy simulation in the ocean', *International Journal of Computational Fluid Dynamics*, 24(10), pp. 393–406. doi: 10.1080/10618562.2010.522527.

Skyllingstad, E. D. and Denbo, D. W. (2004) 'An ocean large-eddy simulation of Langmuir circulations and convection in the surface mixed layer', *Journal of Geophysical Research*, 100(C5), p. 8501. doi: 10.1029/94jc03202.

Smagorinsky, J. (1963) 'GENERAL CIRCULATION EXPERIMENTS WITH THE PRIMITIVE EQUATIONS I. THE BASIC EXPERIMENT', *Monthly weather review*, 91(3), pp. 99–164.

Strandenes, H. *et al.* (2015) 'Comparison of LES and DNS for the flow past a circular cylinder with fairings'. Curran Associates, Inc.

Wijesekera, H. W. (2003) 'Modeling study of turbulent mixing over the continental shelf: Comparison of turbulent closure schemes', *Journal of Geophysical Research*, 108(C3), pp. 1–25. doi: 10.1029/2001jc001234.

Young, M. and Ooi, A. (2007) 'Comparative Assessment of LES and URANS for Flow Over a Cylinder at a Reynolds Number of 3900', *Proc. of the 16th Australasian Fluid Mechanics Conference (AFMC)*, (December), pp. 1063–1070. doi: 10.1080/03610917808812072.

Yue Yin (2014) '3D MORPHOLOGICAL IMPACT MODELLING OF OFFSHORE WIND FARMS USING LES AND HPC', *Coastal eningineering proceedings*, 1(34), p. 48. doi: http://dx.doi.org/10.9753/icce.v34.sediment.48.